

Science with the Space Interferometry Mission

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Abstract. The Space Interferometry Mission (SIM) will be NASA's first dedicated space-based optical interferometer. SIM will produce a wealth of new astronomical data and serve as a technology pathfinder for future astrophysics missions. It will provide 4 microarcsecond (μas) precision absolute position measurements of stars down to 20 magnitude, and the corresponding parallax accuracy allows distance measurements to 10% accuracy on the far side of the Galaxy. With high-precision proper motions derived during its 5-year lifetime, SIM will address a variety of science questions relating to the formation, size, and dynamics of our Galaxy. In this paper we present selected topics from the SIM science program which bear upon determining the extragalactic distance scale.

1. Introduction

The Space Interferometry Mission (SIM) will be a space-based 10-m baseline Michelson optical interferometer operating in the visible waveband. This observatory will be capable of astrometric measurements of unprecedented accuracy, opening up many areas of astrophysics. Over a narrow field of view SIM is expected to achieve a mission accuracy of 1 μas . In this mode, SIM will perform observations as diverse as measuring direct distances to nearby galaxies, and searching for planetary companions to nearby stars, by detecting the astrometric 'wobble' relative to a nearby ($\leq 1^\circ$) reference star. In wide-angle mode, SIM will provide 4 μas precision absolute position measurements of stars, with parallaxes to comparable accuracy, at the end of its 5-year mission. The expected proper motion accuracy is around 2 $\mu\text{as yr}^{-1}$, corresponding to a transverse velocity of 10 m/s at a distance of 1 kpc. Significant improvements in distances to classes of astrophysical objects such as Cepheid variables that are key to establishing the extragalactic distance scale is but one of the contributions that SIM will make to the goal of accurately measuring cosmic distances.

Measuring accurate positions via interferometry reduces, for SIM, to the problem of measuring the interferometer baseline and the optical pathlength difference. The spacecraft architecture (Figure 1) is designed to mitigate the inherent design difficulties by incorporating three interferometers, all sharing the same baseline vector. Collector pods, each containing four afocal telescopes, are located at both ends of the structure. Two of the resulting 10 m baseline telescope pairs observe bright guide stars, to stabilize the optical system, while a third pair observes the science target (the fourth pair serves as a spare). The fundamental astrometric quantity measured by SIM is internal delay required to

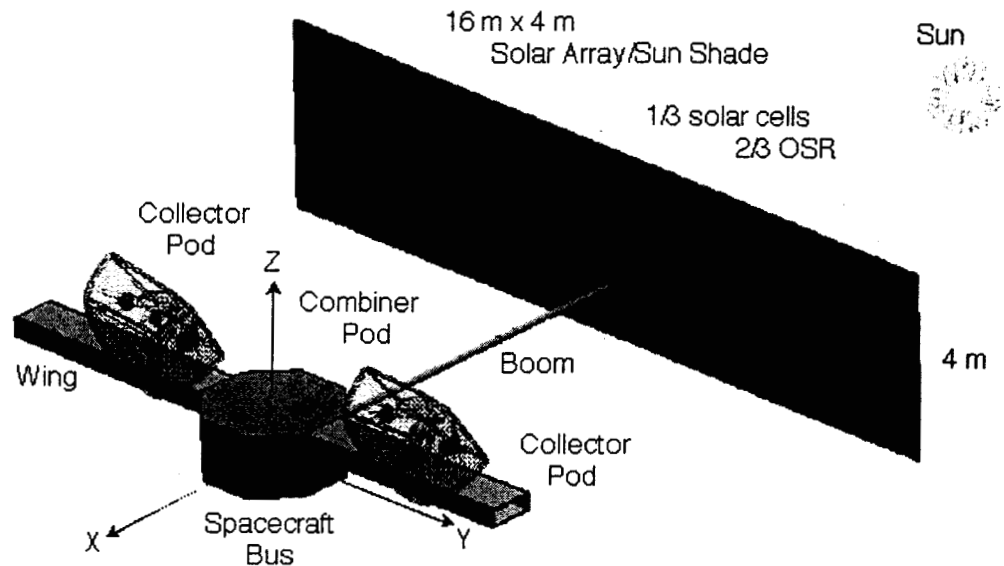


Figure 1. Overview of SIM conceptual design.

yield a white-light fringe, as determined by the internal metrology system. An external metrology system measures the length of the baseline vector, which is defined by corner cube reflectors.

Wide-angle astrometry is performed by measuring the change in white-light fringe delay, between science targets. Measurements with SIM are made by observing science targets in conjunction with objects in a global reference grid. The $4 \mu\text{s}$ SIM grid will form the most accurate astronomical reference system yet. Observations of grid objects serve as the astrometric calibration of the instrument at a particular epoch, as well as the global grid to which science objects separated by angles larger than SIM's 15° field of regard are compared.

By demonstrating new technologies, SIM will serve as a pathfinder for future astrophysics missions which use interferometry. These include precision deployment of optics, active and passive control of structure vibration, alignment and stabilization of optical paths, operation and calibration of the instrument as a space-based interferometer, etc. These are of particular relevance to the proposed Terrestrial Planet Finder (TPF), which will be a large space-based mid-IR interferometer. For TPF, SIM will demonstrate a nulling beam combiner, which operates by applying a polarization flip to one arm of the interferometer. Nulling mode greatly increases the effective sensitivity to circumstellar objects by canceling most of the light from the bright central star (reduction of on-axis light up to 10^{-4} of on-axis light). SIM will also demonstrate rotational synthesis imaging, operating in a mode closely analogous to radio astronomy arrays, and providing 10 milliarcsecond resolution in the optical band.

More information on SIM and the Interferometry Technology Program at JPL is available on the SIM web site at: <http://sim.jpl.nasa.gov>.

2. SIM Astrometric Program Highlights

SIM offers the ability to make astrometric measurements with an accuracy significantly greater than what is possible using ground-based observations, or from any other space mission in the near term. The mission therefore offers tremendous potential for unexpected results, as well as contributing strongly to known problems in a variety of astronomical subfields. With an absolute positional accuracy of $4 \mu\text{as}$, SIM will improve on the best currently available measures (from the ESA Hipparcos mission) by 2 to 3 orders of magnitude, providing parallaxes accurate to 10% and transverse velocities accurate to 0.2 km/s anywhere in the Galaxy, to stars as faint as 20-th magnitude.

The SIM spacecraft design allows a broad science program to be developed, with key parameters are set, not by any one individual scientific objective, but jointly by the set of objectives which constitute the science program. Some specific examples include:

- *Astrometric Detection of Earth-Mass Planets.* SIM will be able to detect the presence, and unambiguously measure the mass, of an earth-mass planet orbiting any of approx. the 100 nearest stars, via the gravitational perturbation it exerts on its parent star, though only a few such targets would be solar-type stars.
- *Detection of Brown Dwarfs and Massive Planets.* SIM will be able to detect sub-stellar companions (gas giant planets and brown dwarfs) around a large sample of nearby stars, and neutron stars and black holes around more distant stars, by measuring their astrometric perturbation on the primary star.
- *Stellar Luminosities and Calibration of Distance Indicators.* SIM will calibrate the luminosities of Cepheid and RR Lyrae 'standard candle' variable stars, and planetary nebulae. These sources are used as standard candles in distance determinations for calculating the Hubble constant, and in distance measurements to globular clusters.
- *Ages of Globular Clusters.* Stellar evolution models for clusters apparently conflict with the age of the universe inferred from the Hubble expansion. SIM will measure the distances to globular clusters directly using trigonometric parallax, yielding a ten-fold improvement in accuracy and allowing the determination of the luminosities of the oldest main-sequence stars.
- *Direct Distance Determination of Nearby Galaxies.* Distances to nearby spiral galaxies can be measured directly via rotational parallax, without use of luminosity-based indicators, using proper motions of their brightest stars due to rotation of the disk about the center of the galaxy.
- *Masses and Evolution of Stars in Close Binary Systems.* By detecting the astrometric signature of the binary star orbit, SIM can determine the masses and orbits of a large number of ordinary binary star systems, as well as more exotic systems: white dwarf/CVs, neutron stars and black holes.

- *Stellar Dynamics of the Galaxy.* Using precision astrometry, SIM will address many fundamental questions concerning the mass distribution in our Galaxy, the dynamics of its stars, and the evolution of its stellar populations.
- *Dynamics of Small Stellar Systems.* By measuring the proper motions of globular clusters, the mass distribution of the Galaxy can be determined. This will help our understanding of the formation of the Galactic halo and the globular cluster system. Tidal tails from disrupted dwarf spheroidal galaxies also provide a powerful means of tracing the Galactic potential.
- *MACHO Gravitational Microlensing Events.* SIM will be able to detect the astrometric signature of microlensing events caused by massive compact halo objects (MACHOs) along the line of sight. Masses for these objects can be inferred, providing important clues to the nature of dark matter in the Galaxy.

In the following sections we present two topics from the proposed SIM science program, to illustrate the importance of distance determination: ages of globular clusters, and rotational parallaxes of spiral galaxies. These show how SIM's capabilities can be used to help improve our understanding of our own Galaxy.

2.1. The Ages of Globular Clusters

Globular clusters (GCs) have ages that are comparable to the age of the Universe, and thus accurate determinations of their ages provide critical tests of cosmological models. Accurate globular cluster ages are also important for setting and interpreting the chronology of the earliest stages of star formation in our Galaxy. (The kinematics of the GC system evoke another whole series of important science issues, which will not be covered here.)

The primary uncertainty in determining the ages of GCs using the " ΔV " technique involves determining the absolute magnitude of the Horizontal Branch (Sarajedini *et al.* 1997). This is usually accomplished by substituting the absolute magnitude of the RR Lyrae stars, a quantity with a very controversial dependence on metallicity. Additionally, reddening must be estimated from integrated color, again depending on the adopted metallicity. Correction for interstellar absorption assumes standard ratios. A direct measurement of distance to a representative set of GCs would eliminate most of the errors in this process, reducing the uncertainties in the age determination by at least a factor of two.

SIM's precision astrometry will be useful in calibrating stellar evolution theory against stars with accurately known masses, luminosities, and pulsation properties. In a summary of current results from globular cluster distance scale fitting, Chaboyer *et al.* (1998) find that the best measured globular clusters have uncertainties in their main-sequence turn-off luminosities of 0.08 magnitudes. This in turn leads to a 1.3 Gyr uncertainty in the age of a globular cluster, which is large enough to span a number of cosmological models and early galaxy formation models. Reducing the uncertainties to the 1% range will distinguish between competing models in both areas. For example, ages of globular clusters known to ± 150 Myr, which is roughly the dynamical timescale for the collapse

of material to form the galaxy, will tell us whether or not the Milky Way was created during such a collapse or through the aggregation of a large number of dwarf galaxies over a substantially longer time. In the context of cosmology, as Mould (1998) has pointed out, the range of ages of the Universe in different models is from 9 Gyr (for $\rho_o = 1$) to 14 Gyr ($\rho_o = 0$). This is the same range as currently measured globular cluster ages. Improving the globular cluster ages will thus directly constrain the possible cosmologies.

GCs in the Milky Way exhibit a range of HR diagram morphologies, perhaps due to a "second parameter", variously identified as a spread in age or in Helium abundance. Determining the distances of a selected group of GCs covering the range of this variation would improve our understanding of its source and our confidence in the reliability of the deduced ages.

Of 150 known globular clusters, over 90% are within 30 kpc of the Sun (see Harris 1996). Measuring the parallax of these clusters ($\geq 33\mu\text{as}$) is easily within the capabilities of SIM, and all but the most reddened clusters have an adequate supply of red giant stars with $V < 18$.

2.2. Rotational Parallaxes of Nearby Spiral galaxies

SIM will precisely and directly measure distances to the nearest spiral galaxies via the technique of rotational parallax. This method, *independent of any intermediate distance indicators* such as Cepheids or RR Lyrae stars, will yield distances with uncertainties at the level of a few percent. Precise knowledge of the distances of nearby galaxies is important for calibrating the cosmic distance scale, understanding the kinematics and dynamics of the local group, and comparing stellar populations in different galaxies.

Because SIM will directly measure the distance to nearby spiral galaxies, it eliminates potential major uncertainties due to luminosity-based distance indicators. It will provide a direct calibration of the Tully-Fisher (Tully 1988) relation used to measure distances to even more distant galaxies. Luminosity calibrations of bright Population I objects in a variety of external systems will then be available, including the full range of Cepheids and RR Lyrae stars observable in nearby spiral systems.

Rotational parallax utilizes the near-circular motions seen in the disks of intermediate to late type spiral galaxies (see Peterson 1995). Measuring the proper motions of individual stars at several locations in the disk of a spiral galaxy, in conjunction with ground-based radial velocity measurements, can provide an independent measurement of the rotation curve at the observed locations, the inclination of the disk, and the distance. Some averaging is required to remove peculiar motions of individual stars, and systematic perturbations to stellar motions due to warping of the disks and the presence of spiral arm structure.

For the nearest spiral galaxies, the desired signal is relatively large for SIM. For example, in the Andromeda galaxy (M31), a transverse velocity of 200 km/s yields a proper motion of about $70\mu\text{as/yr}$. Combining the proper motions with a deprojected velocity map of the galaxy obtained from 21-cm neutral hydrogen mapping then introduces a length scale, which determines the distance to Andromeda.

The goal is to obtain rotational parallaxes to every large spiral galaxy containing individual Population I stars bright enough to be within the observing

limit of SIM. Such a list would include M31, M33, M81, NGCs 55, 247, 253, 300, and 7793. The ideal galaxy is one viewed at an inclination of 45° (so that there is a significance in both proper motion modulations and radial velocities). Nearly edge-on systems can also be used but the inclinations, which enter weakly, will have to be estimated by other means. Results from face-on systems will be limited by the accuracy of the radial velocities.

3. Conclusions

The Space Interferometry Mission will make many important contributions to astronomy and astrophysics during its 5-year mission. Its science objectives include observing programs focusing on the extragalactic distance scale. Among SIM's science highlights are: searching for other solar systems, and studying the process of star and solar system formation; calibrating distance and age indicators used for measuring the cosmic distance scale; directly measuring distances to spiral galaxies, independent of all luminosity-based distance indicators

Acknowledgments. The SIM science program outlined here contains ideas from many people interested in have potential of microarcsecond astrometry, especially the SIM Science Working Group. This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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